

Matching of Ground-Based LiDAR and Aerial Image Data For Mobile Robot Localization in Densely Forested Environments

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Abstract— We present a vision-based method for the autonomous geolocation of ground vehicles or unmanned mobile robots in forested environments. The method provides an estimate of the global horizontal position of a vehicle strictly based on finding a geometric match between a map of observed tree stems, scanned in 3D by sensors onboard the vehicle, to another stem map estimated from the structure of tree crowns observed in overhead imagery of the forest canopy. This method can be used in real-time as a complement to the traditional Global Positioning System (GPS) in areas where signal coverage is inadequate due to attenuation by the forest canopy, or due to intentional denied access. The method presented in this paper has two key properties that are significant: 1) It does not require *a priori* knowledge of the area surrounding the robot. 2) It uses the geometry of detected tree stems as the only input to determine horizontal geoposition.

I. INTRODUCTION

Traditional geolocation of terrestrial vehicles has primarily utilized GPS in different modes to achieve accuracies in the decimeter range (e.g. Differential and Real-time Kinematic techniques) [1]. Despite advances in GPS accuracies and measurement methods, GPS signals are easily attenuated in dense forest environments rendering the service unreliable for continuous and real-time localization purposes. Current efforts in geolocating rovers without GPS focus on dead reckoning techniques that use Inertial Measurement Units (IMU) [2]. Such approaches are prone to drifts in measured position that increase with time; thus posing limitations for rovers operating in close proximity to points of interest.

Techniques such as Simultaneous Localization and Mapping (SLAM) have been utilized successfully to localize rovers in a variety of settings and scenarios [3,4]. SLAM focuses on building a local map of landmarks as observed by a rover and using it to estimate the rover's local position in an iterative way [3,4]. Position errors could be initially high but tend to converge as more landmarks are observed and errors filtered. SLAM therefore does not require *a priori* knowledge of the locations of landmarks or that of the rover. The presented method in this paper is different from SLAM in that it provides a single (non-iterative) estimate of the global position of a rover at a particular pose based on a comparison between landmarks, in this case tree stems, observed by a rover and those analyzed from overhead georeferenced imagery of the forest canopy. In other words, the presented method can be invoked on demand and in a

standalone fashion that could be complementary to the traditional SLAM framework.

The envisioned operational scenario of the presented algorithm is summarized as follows. A rover is initially assumed to be driving autonomously or via teleoperation in a forested area. The rover is anticipated to initially use GPS for localization. However, in situations where the GPS service becomes inaccessible or unreliable, the rover is expected to utilize the method of this paper for the duration of the GPS blackout. In essence, the proposed method is envisaged to act as a backup whenever the primary localization service is down. Alternatively, and to enable real-time redundancy in geoposition estimation, the proposed method could be used in tandem with the primary localization service.

The localization method presented in this paper requires two types of input data. The first are 3D scans of the environment surrounding the rover by onboard Light Detection and Ranging (LiDAR) sensors. At a minimum, the rover is expected to employ a LiDAR with 360° horizontal Field-Of-View (FOV) in order to completely image the geometry of tree stems surrounding the rover. The second data input is an overhead high-resolution image of the exploration site. The overhead image can be acquired either by satellite or aerial means and needs to be orthorectified and geo-referenced. The sequence of operations required for geolocation of a rover using the method of this paper is summarized below:

1. At a particular pose, a LiDAR scan is taken of the area surrounding the rover.
2. LiDAR data is processed to detect and to label tree stems. Tree stem center locations are subsequently estimated and used to create a map of the horizontal locations of tree stem centers relative to the rover.
3. The overhead georeferenced image of the forest canopy above the rover is processed in order to delineate individual tree crowns and estimate tree centers. A map is subsequently generated that contains the absolute horizontal locations of tree stem centers.
4. Maps of tree stem centers estimated from LiDAR and from overhead imagery are matched in this step. The closest match is selected and subsequently used to calculate the rover's horizontal geoposition.

The vision-based localization algorithm is composed of three main components:

- **Tree Crown Identification, Delineation and Center Estimation from Overhead Imagery:**

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Delineates tree crowns and estimates tree centers from the geometric profile of the delineated tree crowns.

- **Tree Stem Center Estimation from Rover LiDAR Data:**

Identifies tree stems and estimates their centers from their 3D profiles.

- **Matching of Tree Centers from Overhead Imagery and LiDAR Data:**

Estimates rover's horizontal geoposition by matching tree center maps generated from LiDAR to those obtained from overhead imagery.

An important aspect in the above formulation of the algorithm is an assumption that deals with the growth profile of trees. In particular, the tree center estimation algorithms for the LiDAR and overhead image assume that the center of the tree crown coincides or is in close proximity to the center of the stem. This implies that for the purposes of this paper, tree crowns are assumed to have a symmetric horizontal profile, while tree stems are assumed to have an upright vertical profile.

This paper is comprised of four main sections. Section II, III and IV discuss the different components of the presented localization algorithm, its properties and constraints. In Section V, test results based on real-world data obtained from an outdoor test campaign are presented and discussed. Concluding remarks are presented in Section VI.

II. TREE CROWN IDENTIFICATION, DELINEATION AND CENTER ESTIMATION FROM OVERHEAD IMAGERY

A map of the horizontal locations of tree stem centers is created from a given high-resolution satellite or aerial georeferenced ortho-photo. The purpose of this map is to provide a basis for comparison to the map generated from stem centers observed in the LiDAR data. Several automatic tree crown delineation algorithms have been previously developed. Wang et al utilizes a multi-step approach where Near Infra-Red (NIR) images are first used to mark tree centers, followed by intensity based segmentation to extract individual tree crowns [5]. Although effective, this approach was not followed because we were interested in developing an algorithm that can work with visible imagery without the need for NIR data.

The main hypothesis that guided the development of the algorithm is the fact that the horizontal location of a tree center in an overhead image can be estimated from the geometric centroid of the delineated crown. That means that if a tree crown is detected and delineated, the tree center location can in principle be deduced with a horizontal accuracy limited to the pixel resolution of the image. Wang et al follows the same hypothesis but augment their algorithm with NIR intensity data of the tree canopy [5].

Figure 1 outlines the process of tree delineation and center estimation using a sample image. First, non-green pixels (i.e. non-vegetation) are filtered out using a simple auto threshold approach. Second, the resultant color image is converted to a grayscale image with 8-bit resolution. With treetops as the

only visible feature in the resulting image, a copy binary image is created and subsequently used in calculating the Euclidean distance transform for all objects in the image. The Euclidean distance transform d between two points (pixels), p and q , is defined as follows (in 2D):

$$d(p, q) = \sqrt{\sum_{i=1}^2 (q_i - p_i)^2} \quad (1)$$

The next step involves applying watershed segmentation to the 8-bit grayscale image with the distance transform as input. The purpose of the distance transform and watershed segmentation is to segment any cluster of treetops into their constituent trees. This step is necessary in the case of dense forests that have touching tree crowns.

Following the segmentation step, the resultant image is composed of delineated tree crowns. The image is subsequently analyzed to estimate centers of trees by calculating the Euclidean centroid of each delineated object. The final product is a map composed of the x and y pixel coordinates of the centroid of each detected crown.

A walkthrough of the algorithm using a sample image is shown in Figure 1. The overhead image used in this example is of a pine forest northeast of Lake Mize in Florida, USA. The image is an orthophoto with 0.3 m resolution (Source: USGS).

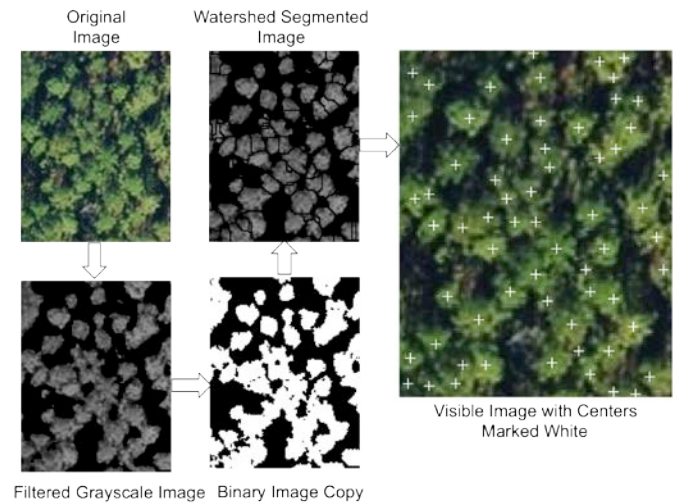


Figure 1: Example Showing Tree Center Estimation Using a Sample Overhead Image of a Pine Forest

Figure 1 shows that for a relatively dense cluster of trees, a visually correct result in terms of the locations of tree centers is obtained. The following are some general constraints:

- Accuracy of estimated tree centers depends on the view angle (perspective) of the image. Therefore for best results and to reduce the effect of parallax, the area of the forest of interest needs to be as close to the nadir of the image as possible.
- The average diameter of a tree crown is recommended to be at least an order of magnitude larger than the pixel resolution of the input image [5]. This means that pixel resolution of an input image needs to be around 0.3 m in order to detect 3 m crowns.

III. TREE STEM CENTER ESTIMATION FROM ROVER LiDAR DATA

As discussed in Section I, the rover is expected to acquire LiDAR data of the forest environment around it for subsequent use by the tree center estimation algorithm. It is noted that the algorithm discussed in this section is based on prior work by McDaniel et al [6].

Based on input LiDAR data such as that shown in Figure 2, the ground plane is estimated first in order to constrain the search space. This is accomplished by tessellating the LiDAR point cloud into 0.5×0.5 m cells across the horizontal plane. Each cell is identified by a unique (row, column) index. Based on the cluster of points within each cell, the point with the lowest height is initially labeled as ground.

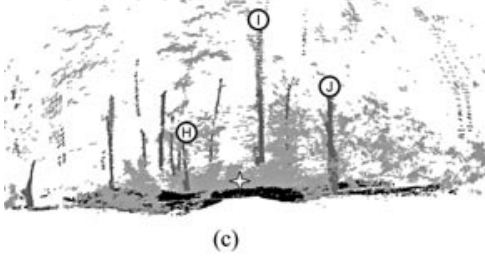


Figure 2: A Sample Showing LiDAR Data of Tree Stems [6]

Due to underbrush, not every point selected in the previous step represents true ground. Therefore, a classifier is utilized to filter data using metrics such as: the number of neighboring points, their geometry and ray tracing scores. Filtered data is then provided to another classifier that utilizes Support Vector Machine (SVM). If a cell contains a point labeled by the classifier, it is treated as true ground. Interpolation is performed for cells that do not have points labeled by the classifier.

The next step involves identifying the extents of stems using threshold and clustering methods. To identify which LiDAR point belongs to the main stem, a simple height-above-ground filter is used. Any points below the selected height threshold are discarded and classified as underbrush. Based on the dataset obtained, the team empirically identified that a height threshold of 2 m is adequate. Filtered data is then clustered following a single-linkage clustering method, which classifies two points to belong to a single cluster if they are in close proximity to each other (within a predefined distance threshold) [7].

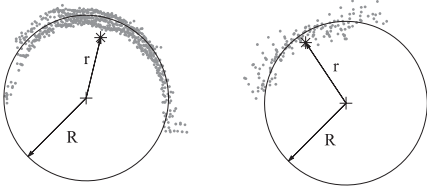


Figure 3: Example Showing Cylinder Fitment [6]

Finally, model cylinders are fit as primitives to the LiDAR data using a least squares scheme (Figure 3). R denotes the radius of the model cylinder while r denotes the estimated radius of curvature of the stem transect containing LiDAR data. The fit between the cylinder primitive and data is found

by solving the following optimization problem where n is the number of points in a cluster, x is the transect containing LiDAR points pertaining to the identified stem and f_i is the distance from the i th point to the surface of the cylinder primitive.

$$\arg \min_{x \in \mathbb{R}^3} = \frac{1}{2} \sum_{i=1}^n f_i^2(x) \quad (2)$$

Following the optimization step, tree stem centers are estimated based on the curvature of each fitted cylinder. Lastly, the location of each estimated tree center in the horizontal plane is incorporated into a tree center map that could be used by the matching algorithm discussed in section IV.

IV. MATCHING OF TREE CENTERS FROM OVERHEAD IMAGERY AND LiDAR DATA

The last component of the vision-based localization algorithm involves matching tree center maps from the LiDAR and overhead image to estimate the horizontal geoposition of the rover. Prior to invoking the matching process, both maps are converted to the WGS84 reference system. The datasets are then provided to an Iterative Closest Point (ICP) algorithm that estimates the horizontal translation and rotation vectors required to fit them together. More precisely, the tree center map derived from the overhead image is treated as the baseline upon which the LiDAR based tree center map is matched to. This is because the map obtained from the overhead image is usually larger than the local map generated from the LiDAR dataset.

The ICP implementation follows the Besl-McKay (point-to-point) framework given as follows [8,9]:

$$\arg \min E_{p,q \in \mathbb{R}^2} = \frac{1}{N} \sum_{i=1}^N (\vec{R} \times \vec{p}_i + \vec{t} - \vec{q}_i)^2 \quad (3)$$

Where E is the average distance error between both maps. R and t are the rotation and translation vectors respectively. P and q are points in the tree center maps generated from the LiDAR and overhead image datasets respectively. N is the total number of points in the LiDAR tree center map. A match is found by employing least squares to find the minimum of the error expression E . Figure 4 shows a sample run of ICP at a single rover pose using data acquired from the Lake Mize site.

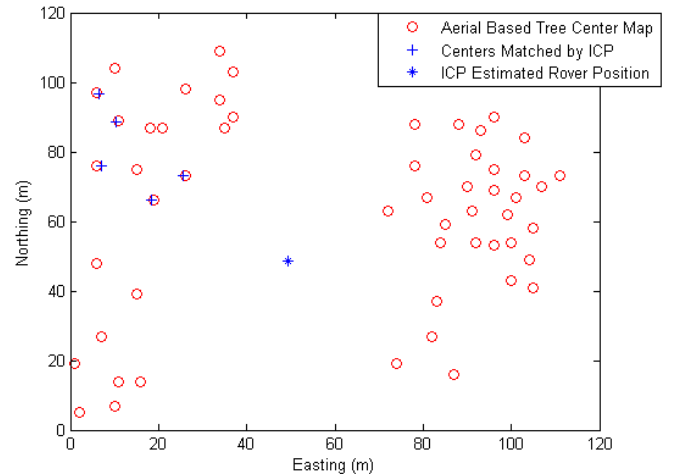


Figure 4: Sample ICP Run for a Single Rover Pose

In Figure 4, the circles denote stem centers generated from the overhead image. The plus signs denote stem centers generated from a single LiDAR file at a particular rover pose. The asterisk shows the estimated rover position as a result of running ICP. As seen in Figure 4, the closeness of the points in both datasets shows that a good match was found. In fact, the match was found with a reported average point-pair accuracy of ~ 1 m (3 pixels). It is noted that in Figure 4, the axes represent easting and northing with respect to a local predefined reference point for that dataset.

The ICP algorithm implemented as part of this paper has the following properties:

- The search space is constrained to a 35×35 m box centered on the last known position of the rover and projected onto the baseline dataset (stem centers from overhead imagery). This optimum search space size was determined following an empirical investigation of the accuracy and processing time performance of ICP using different search space sizes and shapes. In particular, a 35×35 m search space enabled us to maximize position accuracy while minimizing processing time.
- The ICP algorithm always provides a result and produces the best found match along with a cumulative error metric (parameter E in eq. 3). Good candidate matches produce low E while inadequate matches result in a large E . The error E depends on the final cumulative distance error between both datasets and the number of points in the LiDAR based stem center map.

V. RESULTS

The vision-based localization algorithm was completely developed in Matlab and was tested with real-world data. Survey grade LiDAR data was collected of a test site located northeast of Lake in Florida, USA, with coordinates (Lat: $N29.73^\circ$, Long: $W82.21^\circ$). The data was provided by the University of Florida and was acquired by a Leica ScanStation-2 LiDAR system at multiple survey stations within the area bounded by the rectangular box in Figure 5. The area is approximately 110×110 m and the LiDAR dataset has a spatial resolution of approximately 10 cm (on ground). The area is exclusively comprised of pine trees with moderate to dense underbrush. Through manual inspection, 561 tree stems were identified and labeled for benchmarking purposes.

In total, 4 high-resolution orthorectified images of the test site were acquired from USGS. The images were provided in GeoTiff format and were all captured in the visible spectrum. All images were provided in the UTM coordinate system.

Without access to a real rover, and to simulate the envisaged operational scenario, a ground vehicle was simulated in Matlab traveling along a 4-sided polygonal path and using as input the acquired LiDAR data. The simulated rover path is illustrated in red as shown in Figure 5. More specifically, the acquired LiDAR data from the Lake Mize site was gridded using 10×10 m cells that were incrementally fed to the vision based localization algorithm at each pose. Figure 6 shows

the simulated rover path and all identified stem centers in the LiDAR dataset. It is noted that the rover path is composed of 234 poses that are 0.5 m apart.

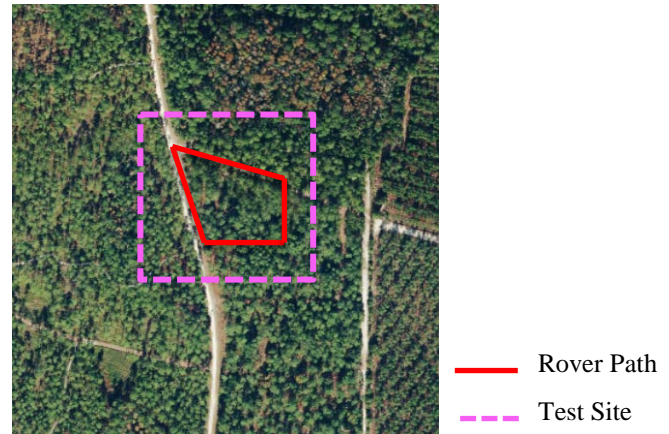


Figure 5: Test Site Northeast of Lake Mize (Source: USGS)

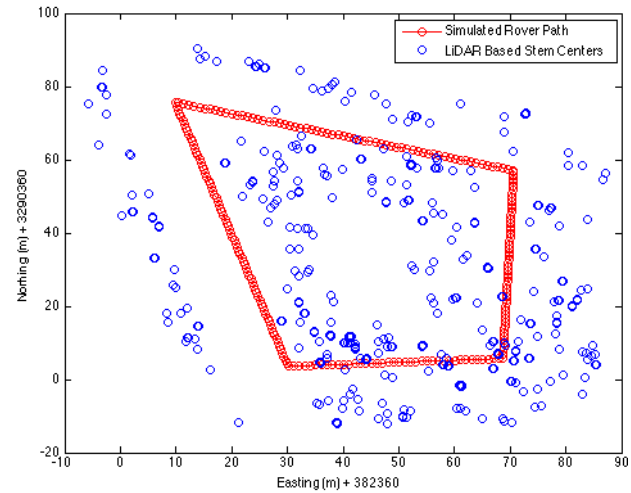


Figure 6: Simulated Rover Path and LiDAR Based Stem Centers

Table 1 summarizes the key properties of the acquired overhead imagery and LiDAR data such as size, resolution and accuracy. It is noted that Aerial Image 1 and 2 were taken of the same area but with different sensors and at different dates.

Table 1: Properties of Data Products Used in Testing

Dataset Type	Properties	Horizontal Accuracy RMS
Aerial Image 1	Visible, 5000x5000 pixels, 0.3 m resolution	2.1 m
Aerial Image 2	Visible, 5000x5000 pixels, 0.3 m resolution	2.1 m
Aerial Image 3	Visible, 8000x8000 pixels, 0.5 m resolution	2 m
LiDAR	0.1 m resolution (Average)	0.01 m

Based on the simulation setup, 3 tests were conducted using the same LiDAR dataset but with 3 different overhead

images as listed in Table 1. In terms of the LiDAR dataset, since it is of high accuracy (1 cm RMS), it was treated as the ground truth upon which geoposition estimates from the vision-based localization algorithm are compared against. More specifically, for each test run, the algorithm's estimated rover position is graphed along with the corresponding GPS location derived from the overlay of the simulated rover path onto the raw LiDAR data. To assess the accuracy of position estimates, the horizontal positional error between the estimate provided by the vision based localization algorithm and the GPS ground truth is calculated. Due to the convergence properties of ICP, the matching algorithm requires an initial estimate of the location of the rover in order to avoid convergence to an incorrect local minimum. Therefore, at the start of the simulation the GPS location of the simulated rover at the first pose is given to ICP as a seed upon which matching is initiated. For subsequent poses, position estimates by ICP of the previous poses are used as seeds. In cases where large jumps in position estimates are observed, the estimate with the least deviation from the average is selected.

4 test runs in total were performed. 3 tests were fully automated (i.e. processing and labeling of input data were all conducted by the vision based algorithm in an end-to-end fashion). One test bypassed the tree crown delineation and center estimation algorithm and instead used a manually handpicked tree center map using Aerial Image 2. This test allowed us to decouple the performance of the vision based tree crown delineation and center estimation algorithm from the overall accuracy performance of the matching algorithm.

Figure 7 and Figure 8 show results from an end-to-end test of the localization algorithm using Aerial Image 2. Figure 9 and Figure 10 show results from the manual test that also used Aerial Image 2. The mean position error and the standard deviation for all test runs are summarized in Table 2. Considering the end-to-end test using Aerial Image 2, the mean rover position error is 4.76 m, which is about 14% of the linear dimension of the 35x35 search space box. In particular, as seen in Figure 8, the majority of rover poses (107 to be specific) resulted in less than 2 m positional error between GPS and the estimation provided by the matching algorithm. This is a good result considering that the spatial accuracy of Aerial Image 2 is 2.1 m RMS. It is noted that due to occlusion by heavy underbrush, no tree stems were detected in several poses. These poses were therefore discarded and shown as gaps in the rover path as seen in Figure 7 and Figure 9.

Three factors play a major role in determining the positional accuracy of the vision-based algorithm: i) Accuracy of the input datasets (aerial and LiDAR). ii) Validity of the tree stem centers estimated from aerial imagery, and iii) Validity of the tree stem centers estimated from LiDAR. The second and third factors are very important in that they can easily affect the positional accuracy reported by the algorithm. If several tree centers were mislabeled the matching algorithm would have difficulties finding the true matches. In cases when erroneous tree centers are present in a data set, ICP would certainly provide a biased result. Online filtering techniques could be used to mitigate this issue. This is part of the scope of upcoming work on the algorithm.

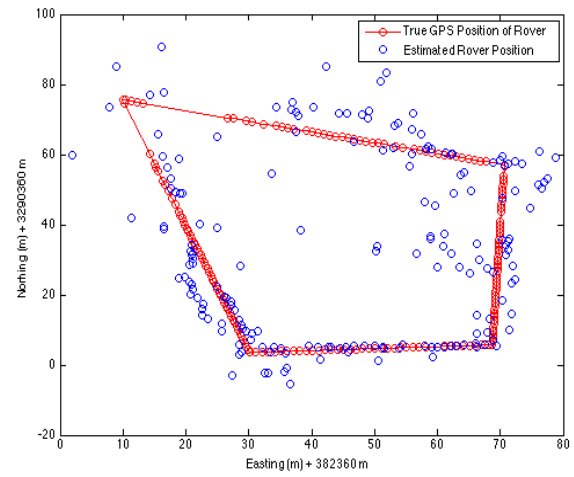


Figure 7: Result from End-to-End Test using Aerial Image 2

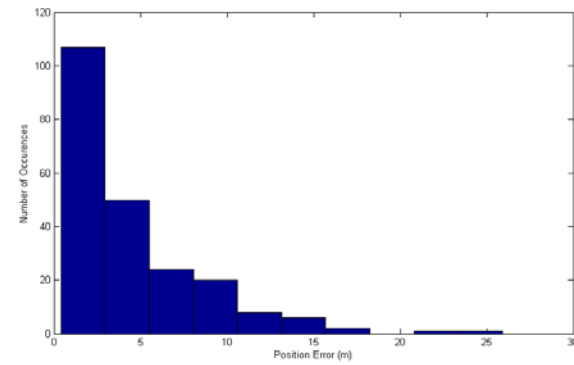


Figure 8: Histogram of End-to-End Test Using Aerial Image 2

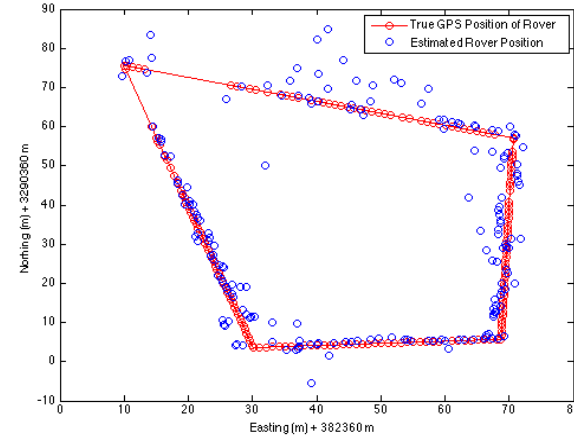


Figure 9: Result from Manual Test Using Aerial Image 2

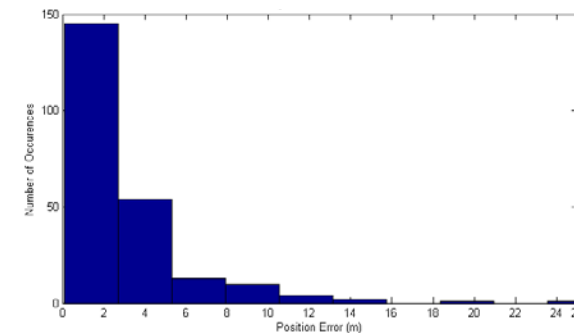


Figure 10: Histogram of Manual Test Using Aerial Image 2

To further understand the effect of mislabeled tree centers on position estimation accuracy, and as discussed previously, a manual test was conducted as a benchmark. Figure 9 and Figure 10 show the accuracy performance of the matching algorithm using a manually handpicked tree center map that was generated from Aerial Image 2. As seen in Figure 9 and Figure 10, geoposition error figures as reported from the manual test showed a much improved performance compared to results obtained from the end-to-end tests. In fact, the mean position error of the manual test was reduced by almost 50% compared to the results from the other tests. Results from all four tests are summarized in in Table 2.

Table 2: Summary of Test Results

Aerial Image	Type of Test	Average Position Error (m)	Standard Deviation (m)
1	End-to-end	5.41	4.42
2	End-to-end	4.76	3.97
2	Manual	2.79	3.38
3	End-to-end	6.83	5.63

From Table 2, it is clear that as the aerial image resolution worsens, the mean position error increases. This is the case with Aerial Image 3. The increase in reported geoposition error could also be attributed to color contrast. Qualitatively speaking, lower Red-Green-Blue (RGB) contrast in an aerial image results in worse delineation results. This has the potential to degrade the map matching performance of the algorithm and hence reduce the accuracy of position estimates.

The difference in performance observed between the end-to-end and manual tests show that the vision based tree crown delineation and center estimation algorithm produces some mislabeled tree centers. Qualitatively speaking, this behavior can be attributed to multiple factors, mainly: i) Tree crowns tend to merge in dense forests rendering the task of delineation tricky and not without uncertainty. ii) Some trees that are visible in the LiDAR dataset may not have visible crowns in the aerial imagery due to occlusions by taller trees. iii) Some trees that are visible in the aerial image may not be visible in the LiDAR dataset due to occlusions by other trees, underbrush or other obstructions. Therefore, operations in dense forests will usually inject certain uncertainties in the estimation of geoposition. Nevertheless, considering situations when GPS is unavailable or unreliable, the benefit of being able to localize using the method of this paper is anticipated to outweigh its reduced accuracy performance.

VI. CONCLUSIONS AND FUTURE WORK

In conclusion, the localization algorithm presented in this paper has the following properties that make it significant: i) It enables rover position estimation by strictly using vision data from ground LiDAR and overhead visible imagery of the area of interest. ii) Does not require external georeferenced landmarks to tie data together or perform corrections. iii) Furnishes a positioning capability that is completely decoupled from GPS to allow uninterrupted

localization in situations when GPS becomes unreliable or inaccessible.

The algorithm presented in this paper is considered a prototype that has constraints and limitations. In this phase of the project, the utility of the algorithm has been verified to provide reasonable horizontal position estimates using real-world data. Future improvements to the positioning accuracy of the algorithm are planned. These will involve improvements to the accuracies of the tree delineation and center estimation algorithm as well as to the LiDAR-based tree stem estimation algorithm. Aerial imagery with higher resolution and accuracy will be acquired to further enhance positioning performance. In addition, online filtering techniques will also be used to smooth position estimates and to discard anomalies. The end goal of the project is to further develop the method of this paper to a level where it is capable of providing geoposition estimates with accuracies that are on par with current GPS standards.

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